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Accuracy evaluation and verification of FISP sediment samplers through CFD modeling

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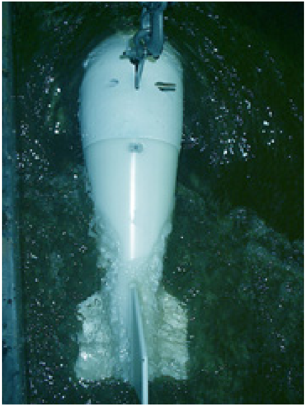
Sponsors: FISP USGS science for a changing world

Outline of the talk

- Introduction
- Configurations
- Modeling framework:
  - Suspended sediment solver
  - Mesh generation
- Results
  - Velocity
  - Sediment concentration
  - Inlet vorticity
- Limitations and future research suggestions
- Conclusions

Introduction

- Main research question: How does the intrusion of the samplers affect the local flow and sediment transport, thus the measurement accuracy?
- Hypotheses:
  - H1: Flow is disturbed by the sampler and therefore the measured sediment concentration deviates from its undisturbed value.
  - H2: Inlet flow through the nozzle has vorticity such that sediment particle could be "swept" out of the flow due to centrifugal force and thus bias the concentration result.



Picture from USGS.gov

Configurations

- Two types of suspended sediment sampler: D95 and D96
- Three different vertical locations in a channel:
  - Upper, close to the free surface
  - Middle
  - Lower, close to the bottom
- Two sediment sizes D_{50}: 150 μm and 300 μm

Geometry preparation

3D Models of the samplers built with FreeCAD

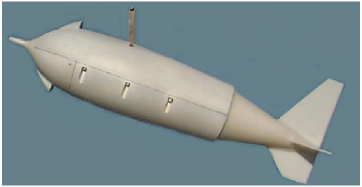


Figure: D96 Sampler Picture

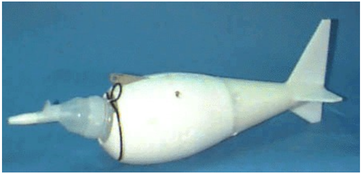


Figure: D95 Sampler Picture

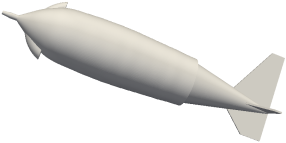


Figure: Modelled D96 Sampler

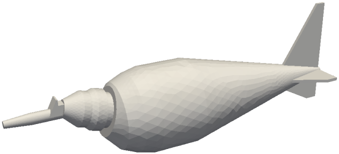


Figure: Modelled D95 Sampler

Channel flow velocity

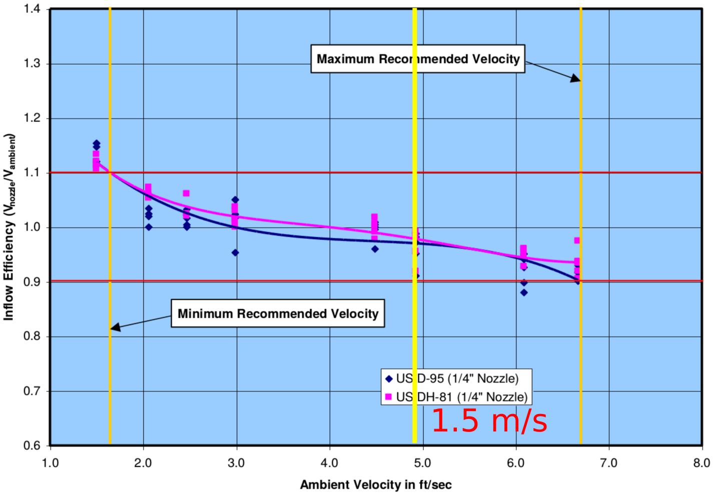
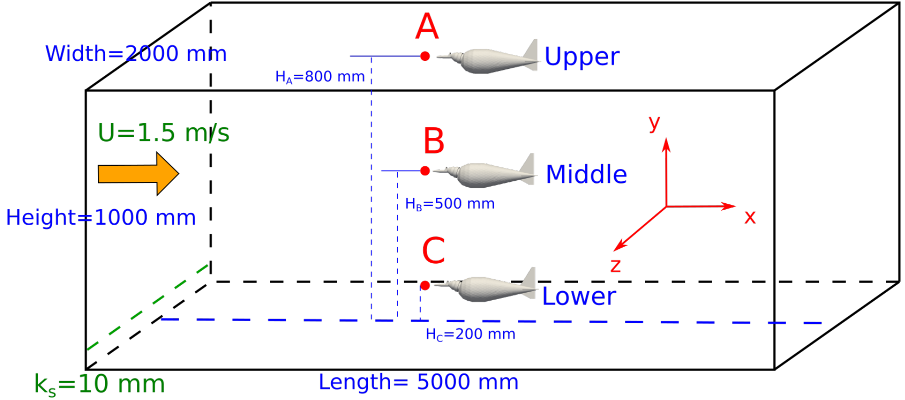


Figure: Inflow efficiency for 1/4 Nozzle, from Report LL, Development of the US D-95 Suspended-Sediment Sampler

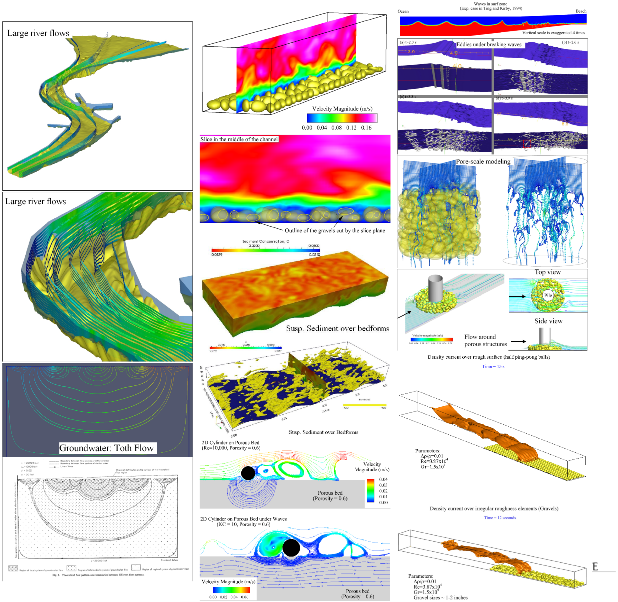
Three vertical locations in the channel



Computational modeling platform

The open source CFD platform OpenFOAM® is used in this project.

OpenFOAM® is designed to capture complex flow features with a wide range of models for turbulence.



Computational modeling platform

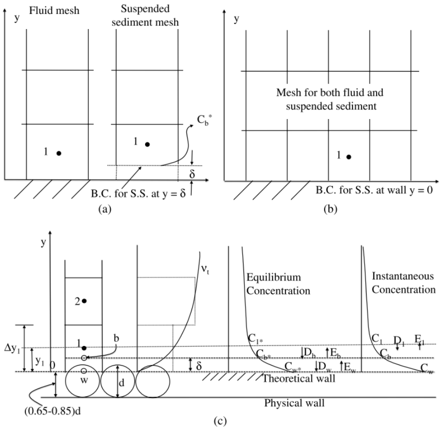
Suspended sediment transport module was added to OpenFOAM, with governing equation as follows (Liu, 2014):

$$\frac{\partial C}{\partial t} + \nabla \cdot [(u + v_s)C] = \nabla \cdot (\epsilon_s \nabla C) \tag{1}$$

where
C is volumetric suspended sediment concentration;
u is flow velocity;
w_s is the sediment settling velocity;
ϵ_s is the sediment diffusivity coeffcient $(= \nu_t/\sigma_c)$;
ν_t is the turbulent eddy viscosity and σ_c is the Schmidt number.

Computational modeling platform

The key is how to deal with the boundary condition at the river bottom.



Treatment of meshes for fluid and suspended sediment:

(*a*) fluid and suspended sediment have different meshes

(*b*) fluid and suspended sediment share the same mesh

(*c*) scheme for the near wall region over a rough bottom

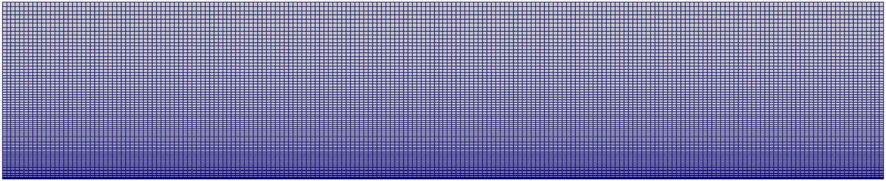
Near-wall grid requirement:

$0.2k_s < y_1 < 0.1H$

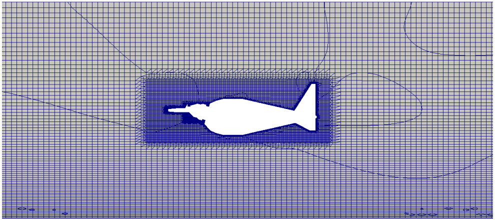
where k_s is roughness height; H is water depth.

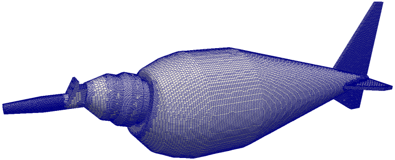
Mesh generation

Use *blockMesh* to create background mesh.



Use *snappyHexMesh* to create the intrusion of the sampler





Background flow field without sampler

- Verify the results by comparing with literature data

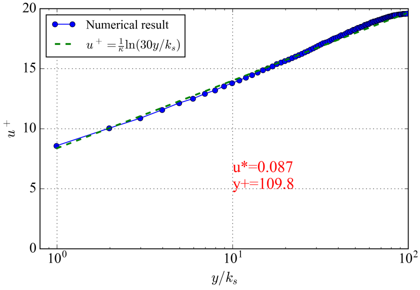


Figure: Flow velocity $y^+ = 109.8$

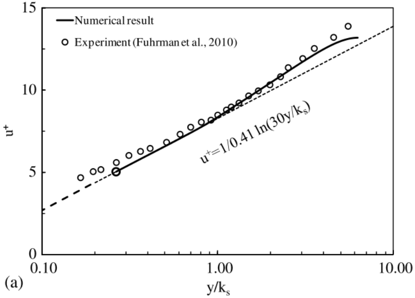


Figure: Liu (2014), $y^+ = 52.5$

Background flow field without sampler

- Verify the results by comparing with literature data

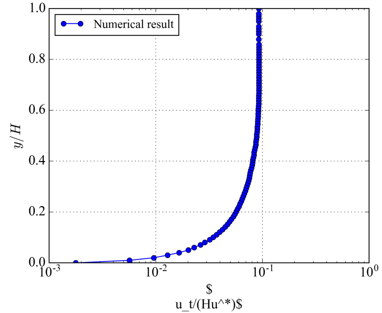


Figure: Eddy viscosity $y^+ = 109.8$

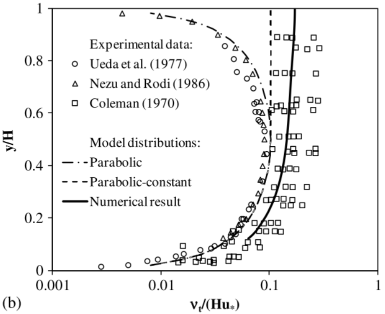


Figure: Liu (2014), $y^+ = 52.5$

Background flow field without sampler

- Verify the results by comparing with literature data

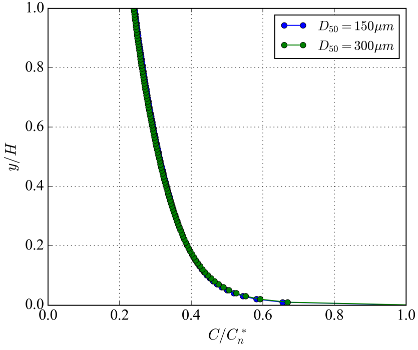


Figure: Sediment $y^+ = 109.8$

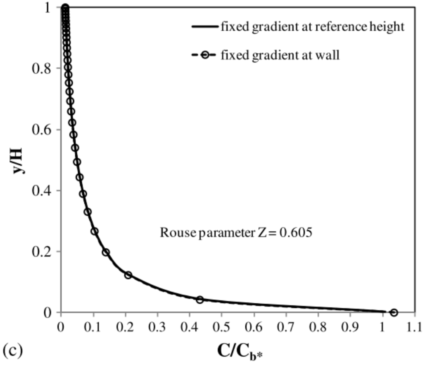


Figure: Liu (2014), $y^+ = 52.5$

Background flow field without sampler

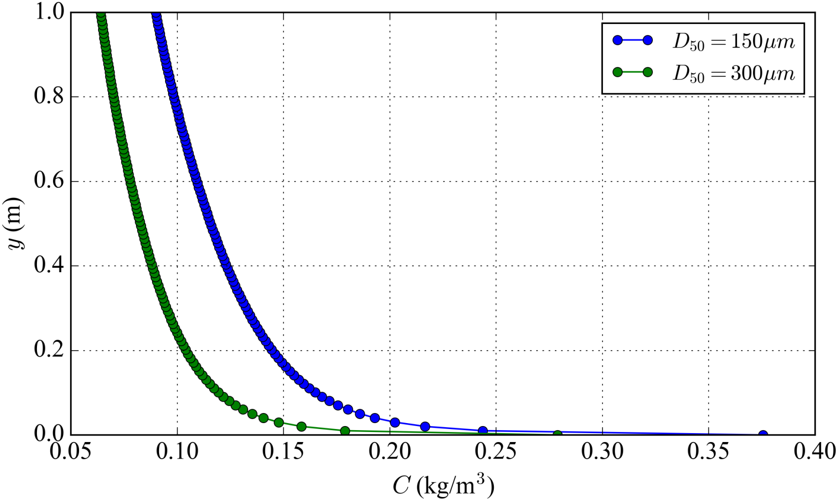
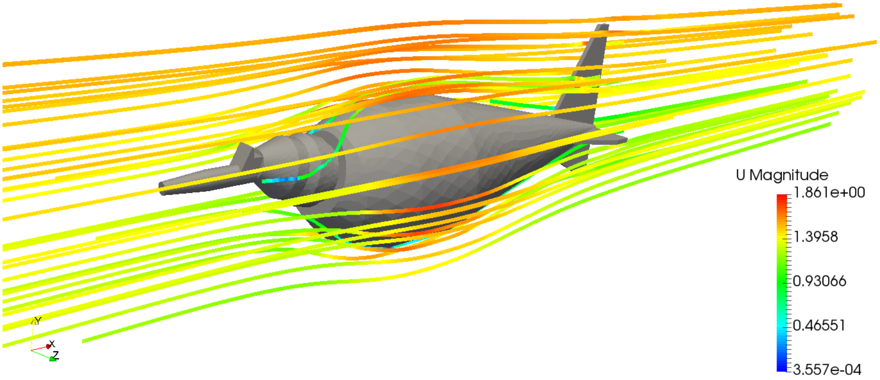


Figure: Vertical distribution of absolute value of sediment concentration

With sampler: streamlines



With sampler: velocity distribution

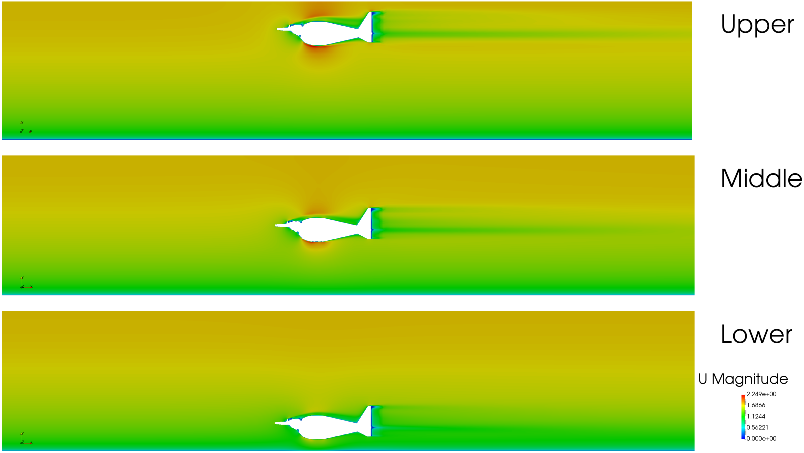


Figure: Velocity distribution on center slice for D95 sampler

With sampler: velocity distribution

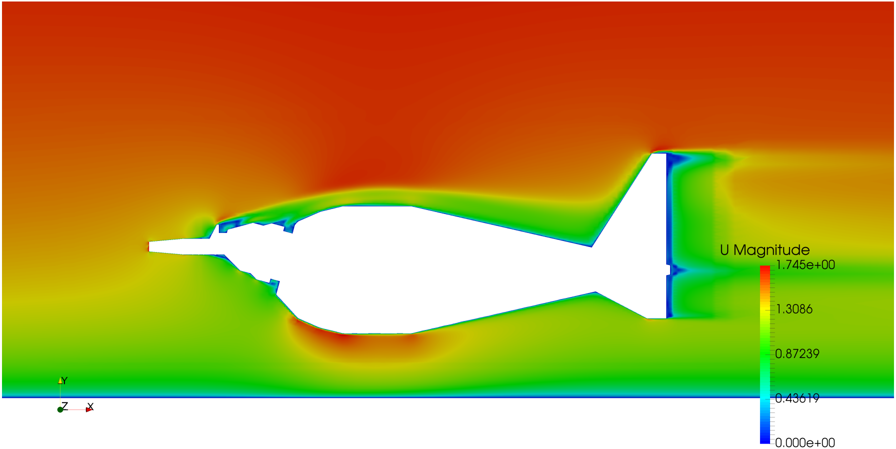


Figure: Zoom in view for the lower configuration for D95 sampler

With sampler: velocity distribution

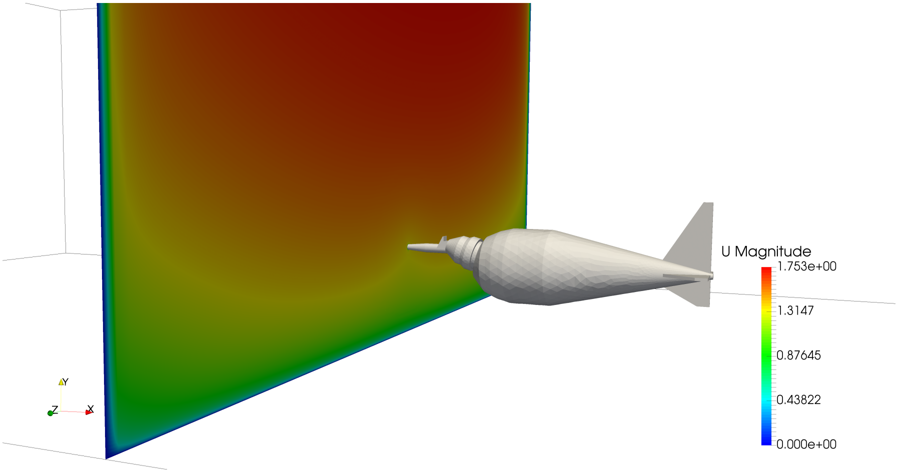


Figure: Cross-section at the inlet nozzle for D95 sampler

With sampler: vertical velocity distribution

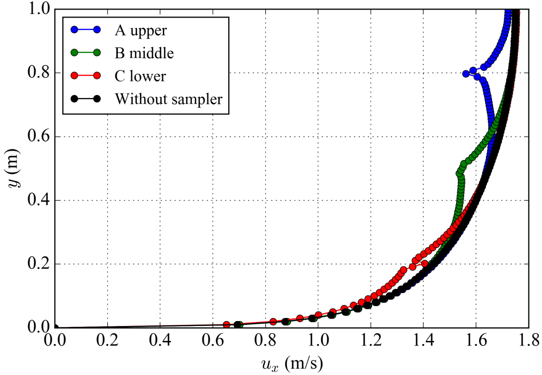
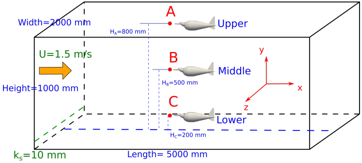


Figure: Vertical distribution of u_x



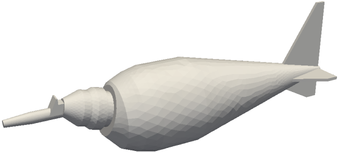


Figure: D95 sampler

With sampler: vertical velocity distribution

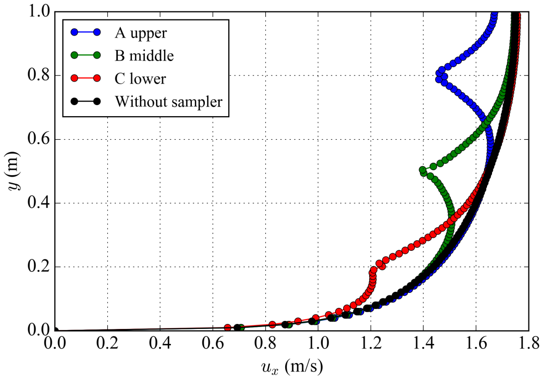


Figure: Vertical distribution of u_x

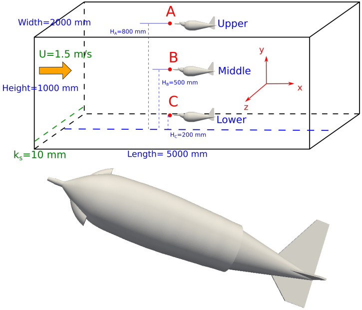


Figure: D96 sampler

With sampler: sediment concentration

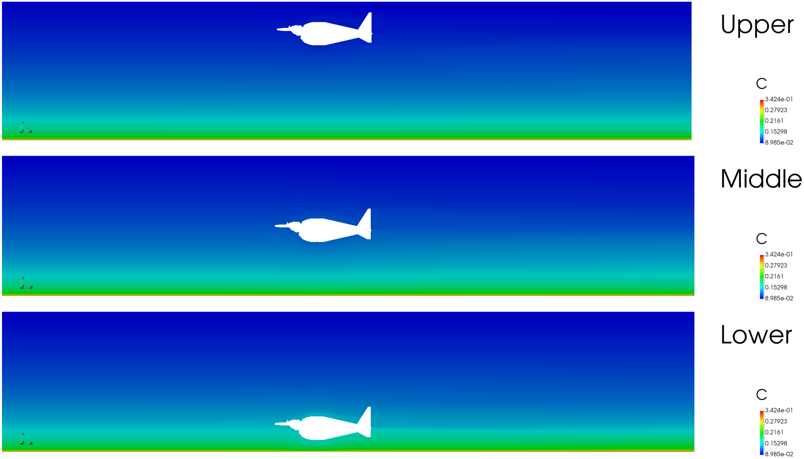


Figure: Contour of sediment concentration, for D95 sampler

With sampler: sediment concentration

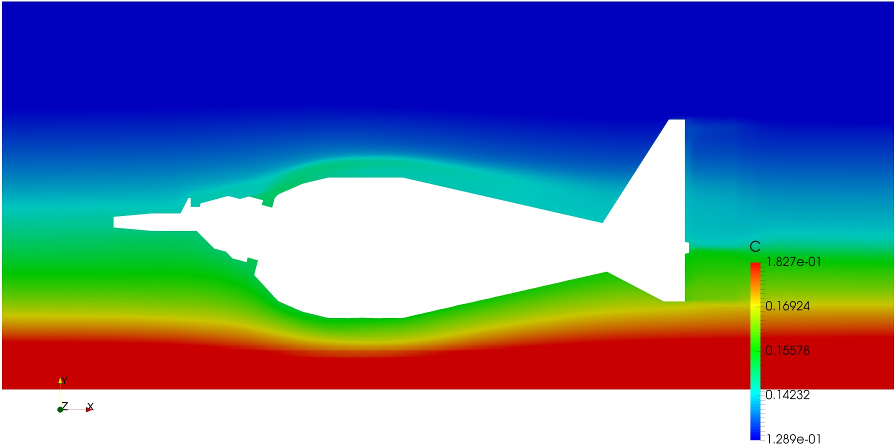


Figure: Zoom in view for the lower configuration, for D95 sampler

With sampler: sediment concentration

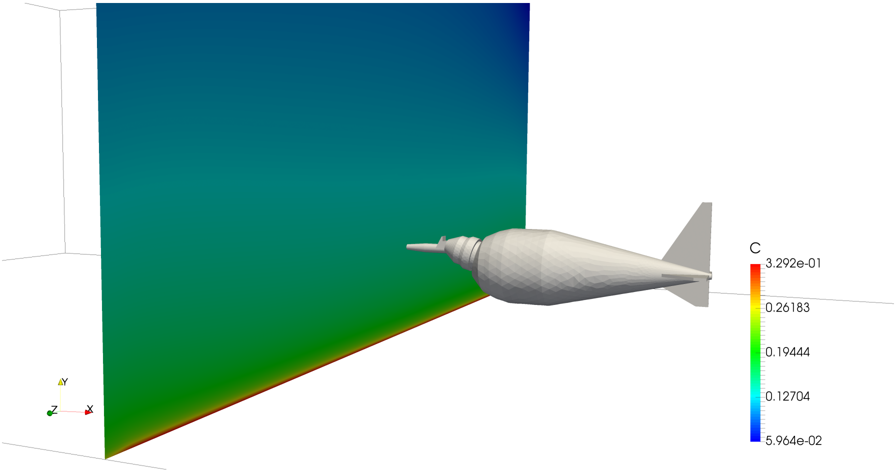


Figure: Cross-section at the inlet nozzle, for D95 sampler

With sampler: sediment concentration

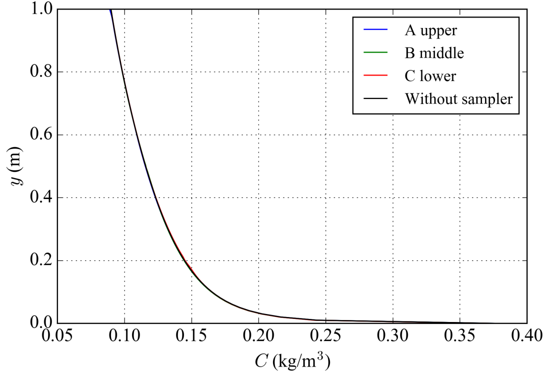


Figure: Vertical distribution at the inlet nozzle,
$D_{50} = 150\ \mu m$

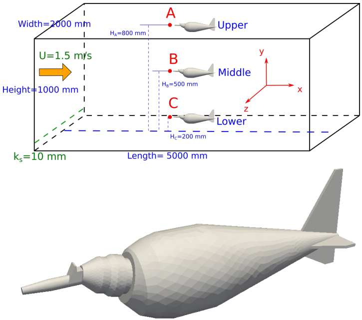


Figure: D95 sampler

With sampler: sediment concentration

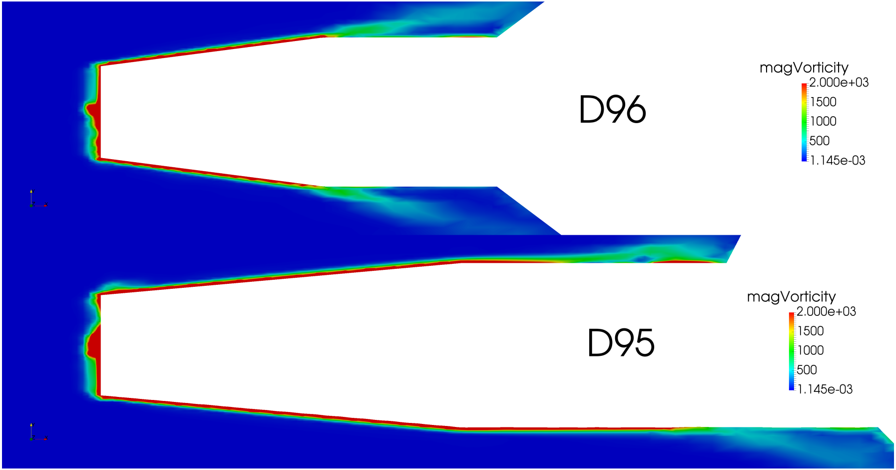
Table: Relative error of the intake sediment concentration

	A Upper	B Middle	C Lower
D95	0.13%	0.05%	0.63%
D96	-0.03%	0.23%	0.67%

Conclusions:

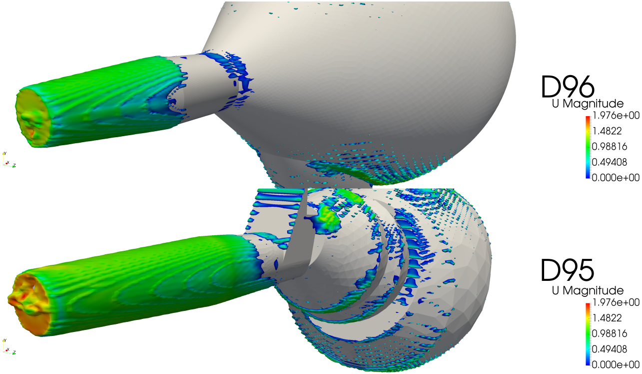
- Hypothesis #1 is NOT true.
- The disturbance to sediment concentration AT THE INLET is below 1%.
- The disturbance to flow field and sediment transport AROUND THE BODY is rather significant.

With sampler: vorticity at inlet nozzle



With sampler: vorticity at inlet nozzle

No persistent swirl was found at the inlet. Thus Hypothesis #2 is not true either.



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Force analysis

Table: Drag force exerted on the sampler

type	position	U_x (m/s)	F_x (N)	F_y (N)
D95	Upper	1.73	3.88	0.44
D95	Middle	1.65	3.95	0.31
D95	Lower	1.44	3.69	0.83
D96	Upper	1.73	7.72	3.06
D96	Middle	1.65	7.41	0.97
D96	Lower	1.44	6.31	0.82

Limitations and suggestions

- Fixed velocity at the inlet nozzle:
  - The inflation of the plastic bag was not modelled, therefore inflow variation was not known
  - Suggestion: a simple flume test and redo the modeling
- "Flight path" effect not considered:
  - Descending and ascending phases are different due to drift angle
  - Based on our results, we guess that disturbance will prorogate to inlet during ascending.
- Only RANS simulation is performed. If we resolve eddies using Large Eddy Simulation:
  - Instantaneous swirl will show at the nozzle.
  - How sediment particles will respond to the instantaneous swirl depends on their inertia. More research needed.
- Only flume test flow condition was used due to the absence of the field data
  - Simultaneous grab samples and flow measurement in field
- The gravity of the sampler is unknown. Otherwise, the drift angle can be compared.

Conclusions

- The sampler disturbs the surrounding flow. But it has very limited influence on the sediment concentration upstream at the protruded inlet.
- No significant swirl found at the inlet using RANS model.

Wrapping up of the project

- Final project report
- A manuscript to *ASCE Journal of Hydraulic Engineering*

Thank you!